General Disclaimer

One or more of the Following Statements may affect this Document

- This document has been reproduced from the best copy furnished by the organizational source. It is being released in the interest of making available as much information as possible.

- This document may contain data, which exceeds the sheet parameters. It was furnished in this condition by the organizational source and is the best copy available.

- This document may contain tone-on-tone or color graphs, charts and/or pictures, which have been reproduced in black and white.

- This document is paginated as submitted by the original source.

- Portions of this document are not fully legible due to the historical nature of some of the material. However, it is the best reproduction available from the original submission.

SENSING OF METEOROLOGICAL VARIABLES BY LASER PROBE TECHNIQUES

FINAL REPORT

National Aeronautics and Space Administration
Grant NGR 22-009-131

covering the period

August 1, 1966 – June 30, 1970

Submitted by: H. J. Zimmermann

June 22, 1970

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Research Laboratory of Electronics
Cambridge, Massachusetts 02139

SUMMARY OF RESEARCH

1. Introduction

Measurement techniques have been developed under this grant for the remote sensing of meteorological variables. These techniques are based on analyses of the light scattered from a laser beam by the various constituents of the atmosphere. Under appropriate conditions, the data obtained with laser radars may be related to the spatial distribution of various minor constituents, such as atmospheric aerosols and trace gases, in addition to vertical profiles of atmospheric density, temperature, and winds.

A variety of problems relating to the meteorology and physics of the atmosphere has been studied under this grant. Additional support for those problems related to the investigation of dust in the upper atmosphere by optical radar was also obtained from NASA through Grant NGR 22-009-114. The results of these studies have been reported in several publications. This final report on NASA Grant NGR 22-009-131 reviews the results of the laser radar studies that were initiated by Professor Giorgio Fiocco and his group at the Research Laboratory of Electronics of Massachusetts Institute of Technology.

2. Research Summary

One of the first and simplest techniques for probing the atmosphere with lasers makes use of the backscattered radiation from a pulsed laser to detect layers of dust particles in the atmosphere. In these experiments, the optical backscattering cross section of the atmosphere is measured as a function of range, and aerosol layers are inferred from significant deviations of the laser echoes expected from dust-free air.

The first experiments in which lasers were used for ground-based remote measurements of atmospheric parameters were conducted at M.I.T. by Fiocco and Smullin.[1] In their preliminary studies echoes from scattering layers from heights of 60-90 km and 110-140 km were detected during the summer of 1963. These echoes were tentatively attributed to dust particles of extraterrestrial origin[2]; this interpretation was corroborated by the observed correlation between the laser radar echoes from 110 to 140 km and ionospheric sporadic-E.[3] Numerical calculations of the ionization resulting from neutral-neutral collisions of the ambient gas induced by incoming extraterrestrial particles[4] verified that the influx of cosmic dust could produce ionization in amounts comparable to that required in the E-region at night and in some types of sporadic-E irregularities. McCormick et al.[5] also reported enhanced scattering from altitudes between 70 km and 140 km and interpreted their measurements as evidence of extraterrestrial dust. It is possible, however, that all of these early results were affected by instrumental difficulties, and the evidence for aerosol layers above the mesosphere might not be reliable.[6-8] Although laser radars with much greater sensitivity have not subsequently detected regions of enhanced scattering above approximately 90 km, it should be pointed out that the influx of extraterrestrial dust could be highly variable. Poultney and Silverberg[9] suggest that the variability of laser radar echoes may be associated with sporadic sources of extraterrestrial aerosols that are due to periodic comets of low inclination. Also, evidence of enhanced meteoric activity during the summer of 1963 has been obtained by techniques other than laser radar.[10,11]

The presence of layers of light-scattering particles near or below the mesopause has been established by numerous visual observations of noctilucent clouds. During the summer of 1964, we performed laser radar experiments in Alaska and Sweden for the purpose of observing the aerosol content of the mesosphere during noctilucent cloud displays.[12] In these experiments strong echoes were observed near 70 km and were taken as an indication that measurable processes involving a wide range of mesospheric heights were involved. New experiments to obtain measurements of the aerosol content of the mesosphere at times when noctilucent clouds might be present were conducted in the summer of 1966 near Oslo, Norway.[13] These measurements indicated that the 60-70 km altitude region contained an appreciable amount of particulate material in the summertime at high latitudes during periods of noctilucent cloud activity, as suggested by our earlier laser radar results. Observations of the transient features of a noctilucent cloud were also obtained with the apparatus: the height of the cloud varied from 75 km to 73 km during the observation interval; the geometric thickness of the cloud was appreciably less than 1 km; and the optical thickness was $\sim 10^{-4}$. An estimate of the meridional flux of particulate material at high latitudes was obtained from the measurements by relating the average vertical distribution of aerosols observed by the laser radar during the summer to the general circulation of the upper atmosphere; estimates of the mass flux of extraterrestrial dust based on these data are in agreement with results obtained by other techniques.

We have also conducted a variety of analytical studies of the dust content of the upper atmosphere. Fiocco[6] has reviewed the previous work directed toward the detection of atmospheric dust by laser radar and has outlined the requirements for a laser radar system to continuously monitor the influx of extraterrestrial dust on Earth. A theoretical study of the meridional circulation of dust in the upper atmosphere has been conducted, and some preliminary results of the study have been reported.[14] The study has been completed and its results will soon be reported.[15,16] By using existing models for the atmospheric meridional circulation and its seasonal variations, possible trajectories of particles of extraterrestrial origin and of radius 0.1 μ to 1.0 μ were obtained. It was found that there are regions of the atmosphere that are not accessible to particles of a given size at certain times of the year, and that there can be a considerable local increase of the particle concentration. Thus the presence of a solid constituent in noctilucent clouds can be related to seasonal variations in the meridional air flow; in fact, the enhancement should be particularly noticeable in the mesosphere during summer for the smaller particles of extraterrestrial origin. Our optical radar observations at high latitudes at times of noctilucent cloud activity confirm a local increase of the aerosol concentration at mesospheric heights.

A two-year study to evaluate the average and time-variant characteristics of stratospheric aerosols has been conducted with a laser radar.[17, 18] Most of the observations were conducted at Lexington, Massachusetts, during 1964 and 1965; some data were also obtained during the summer of 1964 at College, Alaska. The vertical distribution of the aerosol particles was obtained by comparing the laser radar return with the return expected from a molecular atmosphere, using the observed echoes from 25 km to 30 km altitude to calibrate the instrument. The data consistently showed a maximum in the relative concentration of aerosols between 15 km and 20 km altitude. The observations showed that the stratospheric aerosol layer exhibited little temporal variability, with a generally decreasing trend during the two-year observation interval. At the observation site in Lexington, Massachusetts, the observed return from the layer was approximately 1.9 times the expected return from clear, dry air. The daily rms fluctuation of this scattering ratio was approximately 0.3 and hourly fluctuations were smaller. For the observations at College, Alaska, the maximum scattering ratio was ~1.7 with daily fluctuations of ~0.15. The study was conducted during a period following the eruption of the Mount Agung volcano early in 1963; thus, the results may represent anomolous conditions in the lower stratosphere and are likely to be associated with the temporal and spatial distribution of volcanic debris.

The observed scattering ratios have been related to the number of particles per unit volume illuminated by the laser beam by evaluating Mie scattering functions for backscattered radiation. The calculated concentration of $\sim 1\ cm^{-3}$ for particles larger than $\sim 0.3\ \mu$ radius is in agreement with independent studies by other investigators, especially with the particle counts of Rosen.[19] Comparisons with earlier measurements obtained by other investigators using a variety of different techniques indicated that the concentration of stratospheric aerosols was approximately one order of magnitude higher than before the eruption of Mount Agung; this has also been confirmed by the results of other investigators.[20]

The observations have been compared with other meteorological parameters in the lower stratosphere. The center of mass of the layer was usually very close to 16 km; day-to-day changes in the tropopause height were accompanied by a tendency of small vertical displacements of the layer. The laser radar observations performed in Alaska agree with the concept that the height of the layer follows approximately latitudinal changes in the height of the tropopause. A significant negative correlation was found between dust concentrations derived from the results of the laser radar study and ozone concentrations obtained by the Air Force Cambridge Research Laboratories.[21-23] The anticorrelation was also obtained between the measurements of the dust concentration and measurements of total atmospheric ozone obtained at Bedford, Massachusetts; this result provided additional statistical evidence of a relation between the aerosol layer and stratospheric ozone.

Experiments have also been conducted by our group to perform spectral analyses of the light scattered from a laser beam by atmospheric molecules and aerosols. Through the Doppler effect the random motions of the scattering particles will cause the scattered spectrum to be broadened with respect to the radiated spectrum. Analytical investigations of the spectral broadening of light scattered from a laser beam by the gaseous and particulate components of the atmosphere have been performed. The light scattered from a monochromatic beam of light by a low-density gas has a Gaussian frequency spectrum and the spectral width is proportional to the square root of the absolute temperature of the gas; for light at 4880 Å, the wavelength of an argon-ion laser, the full-width at half-maximum of the frequency spectrum will vary from approximately 2.4 GHz to 2.8 GHz over the range of temperatures usually observed in the lowest 10 km of the terrestrial atmosphere. Atmospheric aerosols also contribute to the scattered spectrum; however, their random motions are much slower than the thermal velocities of the air molecules, and the scattered energy from the aerosols is contained in a narrower band of the frequency spectrum than the scattered energy from air molecules. The feasibility of using this technique to separate the effects of aerosol scattering from molecular scattering has been demonstrated by the use of a pressure-scanned Fabry-Perot interferometer to measure the spectral distribution of the light scattered by naturally occurring aerosols in the laboratory air and by artificially produced fogs.[24] The Doppler effect resulting from the motion of scatterers can be utilized in other ways. For example, large Doppler shifts are expected for laser echoes from incoming micrometeorites.[6] Also, since the random thermal motions of atmospheric molecules cause the scattered spectrum to be broadened with respect to the radiated spectrum, measurements of the spectral profile are thereby related to the temperature of the gas and could be used as the basis of a system for remote determinations of atmospheric temperature,[25] while bulk shifts of the scattered spectrum could provide information on wind motion. Furthermore, the spectral width of the aerosol contribution to the laser echoes may be an indicator of atmospheric turbulence.[24,26] The spectral studies of scattered laser radiation have been based on analyses of the light from cw lasers scattered from the volume illuminated by the laser beam. One of our first cw laser scattering experiments was a study of the electron velocity distribution in a reflex discharge.[27-29] The observations indicated a temperature of approximately 30,800°K and 13,570°K for the velocity components parallel and perpendicular to the magnetic field. The anisotropy was related to the randomizing processes in the discharge. An optical homodyne spectrometer[30] has been used to study the spectrum of light scattered from a turbulent fluid. This study utilized an optical homodyne technique whereby low-frequency beats caused by the interference of the various component frequencies that constitute a broadened spectral line are detected by a spectral analysis of the current from a photomultiplier tube to derive information on the frequency spectrum of the incident light.

The homodyne spectrum of coherent light scattered from particles suspended in a turbulent fluid will be broadened with respect to the spectrum observed when the particles undergo Brownian motion in a fluid at rest. A theoretical and experimental study has been conducted to relate measured spectral widths and profiles to the parameters describing the turbulence.

The theoretical analysis suggests that the homodyne spectrum of light scattered from the particles will be determined by the joint probability density function of particle displacements for two particles. When the transit time for the particle moving through the scattering volume is small compared with the Lagrangian integral time scale, the homodyne spectrum, apart from the broadening caused by molecular diffusion, has the same shape as the two-particle, relative velocity distribution. Thus the homodyne spectrum is potentially useful in determining the turbulent velocity distribution.

An optical homodyne spectrometer has been used for an experimental study of the spectrum of coherent light scattered from turbulence induced by a jet of water into water marked with uniform latex spherical particles.[26]

References

1. Fiocco, G., and L. D. Smullin, 1963: Detection of scattering layers in the upper atmosphere (60-140 km) by optical radar. Nature 199, 1275-1276.

2. Fiocco, G., and G. Colombo, 1964: Optical radar results and meteoric fragmentation. J. Geophys. Res. 69, 1795-1803.

3. Fiocco, G., 1965: Optical radar results and ionospheric sporadic E, J. Geophys. Res. 70, 2213-2215.

4. Fiocco, G., 1967: On the production of ionization by micrometeorites. J. Geophys. Res. 72, 3497-3501.

5. McCormick, P. D., S. K. Poultney, U. Van Wijk, C. O. Alley, R. T. Bettinger, and J. A. Perschy, 1966: Backscattering from the upper atmosphere (75-160 km) detected by optical radar. Nature 209, 798-799.

6. Fiocco, G., 1967: Possibility of continuous measurement by optical radar of the influx on Earth of extraterrestrial dust, in The Zodiacal Light and the Interplanetary Medium, Proceedings of a Symposium held January 30-February 2, 1967, at Honolulu, Hawaii, J. L. Weinberg (ed.). NASA SP-150.

7. McCormick, P. D., E. C. Silverberg, S. K. Poultney, U. Van Wijk, C. O. Alley, and R. T. Bettinger, 1967: Optical radar detection of backscattering from the upper atmosphere. Nature 215, 1262-1263.

8. Sandford, M. C. W., 1967: Laser scatter experiments in the mesosphere and above. J. Atmos. Terrest. Phys. 29, 1657-1662.

9. Poultney, S. K., and E. Silverberg, 1969: Mesospheric aerosol concentrations: Theory and experiment. University of Maryland, Department of Physics and Astronomy, Technical Report No. 964.

10. McIntosh, B. A., and P. M. Millman, 1964: Radar meteor counts: Anomalous increase during 1963. Science 146, 1457.

11. Ellyett, C. D., and C. S. L. Keay, 1964: Meteors: An unexpected increase in 1963. Science 146, 1458.

12. Fiocco, G., and G. Grams, 1966: Observations of the upper atmosphere by optical radar in Alaska and Sweden during the summer 1964. Tellus 18, 34-38.

13. Fiocco G., and G. Grams, 1969: Optical radar observations of mesospheric aerosols in Norway during the summer 1966. J. Geophys. Res. 74, 2453-2458.

14. Fiocco, G., and G. Grams, 1969: Motion of Aerosols in the Upper Atmosphere, a paper presented at the Open Meeting of the Cosmic Dust Panel COSPAR Meeting, Prague, Czechoslovakia, 11-23 May.

15. Fiocco, G., and G. Grams: Origin of noctilucent clouds: Extraterrestrial dust and trapped water molecules (submitted for publication, 1970).

16. Fiocco, G., and G. Grams: On the origin of noctilucent clouds (to be presented at Fourth ESRIN-ESLAB Symposium, "Upper Atmosphere Models and Related Experiments," Frascati, Italy, 6-10 July 1970).

17. Fiocco, G., and G. Grams, 1964: Observations of the aerosol layer at 20 km by optical radar. J. Atmos. Sci. 21, 323-324.

18. Grams, G., and G. Fiocco, 1967: Stratospheric aerosol layer during 1964 and 1965. J. Geophys. Res., 72, 3523-3542.

19. Rosen, J. M., 1964: The vertical distribution of dust to 30 kilometers. J. Geophys. Res. 69, 4673-4676.

20. Volz, F. E., 1965: Note on the global variation of stratospheric turbidity since the eruption of Agung Volcano, Tellus 17, 513-515.

21. Hering, W. S., 1964: Ozonesonde observations over North America. Report AFCRL-64-30(I), Air Force Cambridge Research Laboratories.

22. Hering, W. S., and T. R. Borden, Jr., 1964: Ozonesonde observations over North America. Report AFCRL-64-30(II), Air Force Cambridge Research Laboratories.

23. Hering, W. S., and T. R. Borden, Jr., 1965: Ozonesonde observations over North America. Report AFCRL-64-30(III), Air Force Cambridge Research Laboratories.

24. Fiocco, G., and J. B. DeWolf, 1968: Frequency spectrum of laser echoes from atmospheric constituents and determination of the aerosol content of air. J. Atmos. Sci. 25, 488-496.

25. DeWolf, J. B., 1967: On the Measurement of Atmospheric Temperature by Optical Radar. S. M. Thesis, Massachusetts Institute of Technology, Cambridge, Mass.

26. DeWolf, J. B., 1969: Homodyne Studies of Light Scattered from a Turbulent Water Jet. Ph. D. Thesis, Massachusetts Institute of Technology, Cambridge, Mass.

27. Koons, H. C., 1968: Laboratory Investigation of Low-Density Plasmas by Continuous-Wave Laser Scattering. Ph. D. Thesis, Massachusetts Institute of Technology, Cambridge, Mass.

28. Koons, H. C., and G. Fiocco, 1968: Anisotropy of the electron velocity distribution in a reflex discharge measured by continuous-wave laser scattering. Phys. Letters 26A, 614-615, 6 May.

29. Koons, H. C., and G. Fiocco, 1968: Measurements of the density and temperature of electrons in a reflex discharge by scattering of cw Ar^+ laser light. J. Appl. Phys. 39, 3389-3392.

30. Dubin, S. B., J. H. Lunacek, and G. B. Benedek, Observations of the spectrum of light scattered by solutions of biological macromolecules. Proc. Natl. Acad. Sci. U.S. 57, 1164-1171 (1967).

3. Publications

Journal Papers

Fiocco, G., 1965: Optical radar results and ionospheric sporadic E. J. Geophys. Res. 70, 2213-2215.

Fiocco, G., 1967: On the production of ionization by micrometeorites. J. Geophys. Res. 72, 3497-3501.

Fiocco, G., 1967: Possibility of continuous measurement by optical radar of the influx on Earth of extraterrestrial dust, in The Zodiacal Light and the Interplanetary Medium. (Proceedings of a Symposium held January 30-February 2, 1967, at Honolulu, Hawaii, J. L. Weinberg, ed.), NASA SP-150.

Fiocco, G., and J. B. DeWolf, 1968: Frequency spectrum of laser echoes from atmospheric constituents and determination of the aerosol content of air. J. Atmos. Sci. 25, 488-496.

Fiocco, G., and G. Grams, 1967: Optical radar and airglow observations during noctilucent cloud displays (Abstract). Trans. Am. Geophys. Union 48, 188-189.

Fiocco, G., and G. Grams, 1969: Optical radar observations of mesospheric aerosols in Norway during the summer 1966. J. Geophys. Res. 74, 2453-2458.

Fiocco, G., and G. Grams, 1969: Motion of aerosols in the upper atmosphere, a paper presented at the Open Meeting of the Cosmic Dust Panel, COSPAR Meeting, Prague, Czechoslovakia, 11-23 May.

Grams, G. W., 1969: Laser radar measurements of the aerosol content of the atmosphere, in Atmospheric Exploration by Remote Probes, Vol. 2, pp. 207-212 (Proceedings of the Scientific Meetings of the Panel on Remote Atmospheric Probing, April 18-20 and May 16-17, 1968). Final Report of the Panel on Remote Atmospheric Probing to the Committee on Atmospheric Sciences, National Academy of Sciences, National Research Council, January.

Grams, G., and G. Fiocco, 1966: Studies of stratospheric aerosols and correlations with ozone (Abstract). Trans. Am. Geophys. Union 47, 127.

Grams, G., and G. Fiocco, 1967: Stratospheric aerosol layer during 1964 and 1965. J. Geophys. Res. 72, 3523-3542.

Koons, H. C., and G. Fiocco, 1968: Measurements of the density and temperature of electrons in a reflex discharge by scattering of cw Ar^+ laser light. J. Appl. Phys. 39, 3389-3392.

Koons, H. C., and G. Fiocco, 1968: Anisotropy of the electron velocity distribution in a reflex discharge measured by continuous-wave laser scattering. Phys. Letters 26A, 614-615, 6 May.

Theses

John B. DeWolf, "On the Measurement of Atmospheric Temperature by Optical Radar," S. M. Thesis, Massachusetts Institute of Technology, Cambridge, Mass., 1967.

John B. DeWolf, "Homodyne Studies of Light Scattered from a Turbulent Water Jet," Ph. D. Thesis, Massachusetts Institute of Technology, Cambridge, Mass., 1969.

Gerald W. Grams, "Optical Radar Studies of Stratospheric Aerosols," Ph. D. Thesis, Massachusetts Institute of Technology, Cambridge, Mass., 1966.

David F. Kitrosser, "A Night Airglow Study of the Hydroxl (OH) Rotational-Vibrational Molecular Spectra in the (8, 3) Sequence and Its Diurnal Temperature and Intensity Variation," S. M. Thesis, Massachusetts Institute of Technology, Cambridge, Mass,, 1968.

Harry C. Koons, "Laboratory Investigation of Low-Density Plasmas by Continuous-Wave Laser Scattering," Ph. D. Thesis, Massachusetts Institute of Technology, Cambridge, Mass., 1968.